Systematic Earth Observation: Significant Progress as We Enter the 21st Century with Landsat 7

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ABSTRACT

The Landsat Earth observation approach introduced in 1972 created a new way of monitoring land cover and land use globally. The Landsat 7 mission, successfully launched on April 15, 1999, continues those observations and demonstrates significant progress in precise numerical radiometry, spectral differentiation and seasonally repetitive monitoring as we enter the 21st century. A long-term data acquisition plan was designed to ensure that substantially cloud-free, seasonal coverage would be recorded and archived in the U.S. for all land areas of the globe. Substantial improvements in calibration procedures have also been made to ensure long-term stability in the acquired spectral radiometry. A Landsat Science Team consisting of representatives from U.S. universities and government agencies has been addressing the technical and analytical means to process and analyze the core of this observation record. The expected outcome of these efforts is a rapid improvement in understanding the Earth system, as well as conceptual knowledge that will underpin significant advancements in the application of this technology for commercial, operational, educational and research purposes. The lessons learned from the Landsat 7 mission are expected to have a significant, positive influence on future Landsat-like missions.

I. INTRODUCTION

The terrestrial Earth Observatory, Landsat, originated use of space platforms for observing the Earth's land areas. Conceived in the 1960's and first deployed in 1972, a series of 7 satellites (6 have been successful – Landsat 6, a non-NASA mission, failed to reach orbit) have provided a continuous record of detailed land conditions for nearly three decades. The conceptual foundations for the mission in fact extend back more than a century when cameras where first deployed on hot air balloons, pigeons, kites and other aerial vehicles to record the spatial patterns of land cover. Initially, the Landsat mission extended aerial photography into space. The earliest Landsat sensors, the Return Beam Vidicon and Multispectral Scanner System (MSS) were designed as electronic equivalents to color infrared chemical photography. However, as the mission matured and more researchers used the numerical, digital record from the MSS sensor, a new perspective on the science value of this observatory evolved. Spectral vegetation indices now pursued using data acquired by Landsat, SPOT, AVHRR, Vegetation, IRIS, MODIS, ASTER, IKONOS, etc. originated in our appreciation that the Landsat observatory provided a new means to study the Earth's environmental systems, specifically as related to ecological processes and photosynthetic activity.

The key value of the Landsat observatory is that it acquires data that discriminates between natural and human activities on the Earth by not only providing detailed spatial views, but by also capturing the seasonal dynamics of the biosphere. If image acquisitions are planned carefully, and a robust, calibrated archive is maintained, an invaluable data set can be created in a manner that permits differentiation between seasonal trends of the Earth system and long-term secular trends brought about by human activities and environmental change. In the remainder of this short paper, we will touch upon some of the new approaches that were implemented in the Landsat 7 program to ensure that a robust, calibrated archive of Earth observation data were acquired to meet the demands of researchers today, and far into the future.

II. MISSION CONFIGURATION

A. Instrument: The only instrument carried on Landsat 7 is the Enhanced Thematic Mapper Plus (ETM+). The ETM+ is similar to the Thematic Mappers flown on Landsat's 4 and

5, but with a few important changes incorporated into its design. These include the addition a high resolution (15 m) panchromatic band, an increase in the spatial resolution of the thermal band from 120 m to 60 m, and the addition of two calibration devices to improve the radiometric calibration of the data.

B. Data Flow: ETM+ data acquired for the U.S. archive are either down-linked in real-time, or stored in a solid state recorder for later downlink to one of three U.S.-operated ground receiving stations located near Sioux Falls, South Dakota, Fairbanks, Alaska, or Svalbard, Norway. Eventually, all of the data are sent to the USGS EROS Data Center (EDC) in Sioux Falls, S.D. for data processing, archive, and distribution.

C. Data Acquisition: Taking the pulse of the planet in a scientifically meaningful way involves looking at all aspects of the global ecosystem, including volcanoes, glaciers, agricultural areas, tropical humid rainforests, coral reefs, oceanic islands, and sea ice. A primary goal of the Landsat 7 mission was to acquire and periodically refresh a global archive of sunlit, substantially cloud-free land scenes that captures this "pulse of the planet." This mission statement, while sounding rather straightforward, presented a number questions to the implementers: How often is "periodic"? What defines "sunlit"? How many clouds are allowed in a "substantially cloud-free" scene and how do we avoid them? What is a "land scene"?

The Landsat 7 Long Term Acquisition Plan (LTAP) was developed to systematically answer these questions. For each scene, it specifies:

- whether the scene is **land** or water;
- the **seasonality** to be applied throughout the year, defined as acquisition rate ("once" or "every opportunity") over a given period of time ("season");
- the best **gain** setting for the time of year;
- the historical cloud cover (**climatology**) which is used in concert with cloud forecasts to determine whether to schedule the scene for acquisition; and
- the range of **sun angles** for daylight imaging.

The LTAP has been one of the major successes of the Landsat 7 mission. Having completed forty-one 16-day cycles between June 28, 1999 and April 15, 2001, over 148,000 images had been acquired and archived at EDC. Nearly 51,000 scenes, or 36%, exhibited 0 – 10% cloud cover, with an additional 24,000+ scenes, or 17%, having between 11 – 30% cloud cover. A complete, global cloud-free archive of imagery already exists, and in most cases the stack of highly usable scenes for any given location is many, many layers deep. For a more in-depth description of the LTAP strategy, please search for articles by T. Arvidson, J. Gasch, and/or S. Goward, et al.

III. INSTRUMENT / SYSTEM PERFORMANCE

Landsat 7 has been in orbit for two years as of April 15, 2001, and operationally providing calibrated data products for two years as of June 28, 2001. A radiometric calibration team consisting of scientists and analysts from the Landsat Project Science Office at NASA GSFC, the Landsat 7 Image Assessment System at EDC, and from four universities has been created to evaluate ETM+ calibration based on on-board and ground-based (vicarious) calibration methodologies. The results are assembled and compared semi-annually and the calibration parameter files are adjusted as necessary. To date, this team of analysts has not detected any major change from pre-launch calibration values for the reflective bands, and absolute at-sensor radiometric accuracy appears to be within 5%. For the thermal band, their vicarious calibration results indicated a bias, with the ETM+ derived temperatures being about 3K degrees too high. The calibration parameter file was updated October 1, 2000 to remove this bias, however the Landsat Product Generation System (LPGS) software at EDC required modifications that were not incorporated until December 30, 2000. All data products generated since this date have the correct thermal band calibration, regardless of image acquisition date, with uncertainties at the 1% level.

An additional benefit of Landsat 7 calibration activities has been the underfly of Landsat 5 by Landsat 7 shortly after launch. This has enabled a rigorous cross-calibration between Landsat 5 TM and Landsat 7 ETM+, which in turn has produced the first reliable calibration for 1990's era Landsat 5 data.

The geometric performance of the Landsat 7 mission has also exceeded system-level performance goals. A geodetic registration accuracy of 50 m (compared to a goal of 250 m) is being attained routinely when post pass ephemeris data are utilized in the generation of Level 1 data products.

The consensus opinion of the Earth observation calibration community is that the Landsat 7 ETM+ is perhaps the most stable and well-calibrated, high-resolution sensor ever placed in orbit. See the article elsewhere in these proceedings by B. Markham et al., for a more in-depth discussion of ETM+ radiometric calibration. For a more in-depth description of geometric calibration, please search for articles by J. Storey et al.

IV. LANDSAT SCIENCE TEAM INITIAL RESULTS

The basic science mission of Landsat 7 is to monitor changes in Earth's land-cover, understand the origin of those changes, and assess the consequences for the Earth system. Land-cover, in the broadest sense, encompasses all of the elements making up the terrestrial environment, including forests, deserts, farmland, cities, and ice caps. These elements interact with both the climate system (through exchanges of energy, gases, and water) and the socio-economic system by which humans make their living. While year-to-year changes in land-cover may be small, and require Landsat-type resolution to resolve, the cumulative effects of these changes may be substantial enough to affect the global climate regime. As one example, tropical deforestation typically occurs as isolated zones of logging, clearing, or road building, with a length-scale of only 10 - 100 meters. However, when integrated over the globe, tropical deforestation is thought to contribute about 20% of the total anthropogenic emissions of CO_2 to the atmosphere.

In order to fully exploit Landsat observations for global change science, in 1996 NASA selected and funded the Landsat Science Team. The team is composed of fourteen members from U.S. universities, civil agencies, and NASA field centers. In addition to Earth science research, the team is actively engaged in remote sensing science, including vicarious calibration of the ETM+, cross-calibration with other sensors, and improving methods for atmospheric correction and image registration. Although the team will conclude its activities in June, 2001, a forthcoming volume of *Remote Sensing of the Environment* will highlight initial results from team members.

A few examples are included here to illustrate the breadth of research being carried out by the Landsat Science Team, and the linkage between the global Landsat archive and the key science questions addressed by this significant global monitoring resource.

- Dr. David Skole, (Michigan State University) has been applying the 29-year Landsat data record to quantify rates of deforestation in the Amazon basin and Southeast Asia. Revised estimates for logging and degradation (so-called "cryptic" deforestation) from Landsat analysis amount to 2700-4200 km^2/yr for 1992-1996 considerably lower than previously published estimates.
- Drs. Frank Mueller-Karger and Serge Andrefouet (University of South Florida) have initiated a pilot program to map the biogeography of 84 coral reefs in French Polynesia. Although coral reefs account for much of the biodiversity of the oceans, never before has there been sufficient high-resolution data to mount such a comprehensive mapping and monitoring program.
- Dr. Alexander Goetz (University of Colorado) has mapped agricultural practices in the High Plains of the Western United States from 17 years of Landsat data, revealing systematic shifts in the distribution of pivot irrigation systems in response to regional farming conditions and water availability. He has also produced a model to predict susceptibility to sand-dune reactivation in the High Plains, which could occur with greater frequency in a warmer, dryer climate.
- Dr. Robert Bindshadler has mounted a comprehensive mapping program for Antarctica, with a particular emphasis on understanding the dynamics of ice shelves. As part of this mapping, Dr. Bindshadler recently discovered a major new crack in the Pine Island glacier that will lead to the formation of a new "super iceberg."

These examples demonstrate how Landsat-based science is evolving. While such research in past decades relied on using only one or two scenes, these new studies analyze changes in entire ecosystems, thus bridging the gap between local phenomena and global changes in climate and habitability.

V. CONCLUSIONS AND FUTURE DIRECTIONS

The key value of the Landsat observatory is that it provides a data set that permits the unique identification of both human and natural changes within the Earth's environment, capturing both spatial patterns of change as well as the seasonal dynamics of the biosphere. For Landsat 7, data acquisitions are being done in a manner that will permit differentiation between seasonal trends of the Earth system and long-term trends brought about by human activities and environmental change.

Landsat imagery has dazzled the user community from the very beginning of the mission series in 1972, and this has often caused questions to arise as to whether such information is of sufficient "value" to be the basis of commercially viable business opportunities. We have already lived through more than a decade (1985-1999) when the Landsat system was turned over to the commercial sector to explore this possibility. This was not a success. The Landsat 7 mission represents a return of the mission to government oversight and operations (NASA/USGS). This activity has been a stunning success and lays the foundation for more advanced technologies and mission concepts in the future. However, there remains considerable pressure to explore the commercial possibilities of this technology. At the moment the discussions surrounding the Landsat Data Continuity Mission (LDCM) point toward primary interest in having these observations supplied to the science community from the private sector by the 2005 / 2006 timeframe. Current plans call for a data buy arrangement, in which a commercial company will build, launch, and operate the LDCM, while the USGS and NASA will purchase science data to continue to populate a robust national archive. How such an enterprise is implemented will be of critical importance to the science value of the observations, as well as the economic potential of the enterprise. An initial draft of the LDCM data specification has been released, and can be viewed at: http://ldcm.usgs.gov.